

SECTION V

Geology and Hydrogeology

The geological suitability of a specific interval for the injection and confinement of various non-hazardous waste waters is primarily determined by the following criteria:

- Lateral extent, thickness, porosity, and permeability of the injection reservoir
- Lateral extent, thickness, porosity, and permeability of the overlying aquicludes in the injection zone and confining zone
- Mineralogical composition of injection reservoir, overlying aquicludes, and confining zone
- Faulting or fracturing of injection reservoir, overlying aquicludes, and confining zone
- Seismic risk:

These criteria are determined by the regional and local depositional and structural histories of the geologic section.

The **Eocene sands** of the **Cockfield Formation** provide an excellent injection reservoir in terms of its petro-physical characteristics, mineralogic composition, and areal extent. The **Cockfield** has sufficient porosity, permeability, thickness, and lateral continuity to accept and contain injected fluids. In the area surrounding the TexCom WDW-315 well (WDW-315) the overlying confining layers of the **Jackson Formation** and the underlying **Cockfield Shale Member** are free of transecting, vertically transmissive faults and fractures and are sufficiently thick, impermeable, and laterally continuous to confine the waste water.

In the following sections, the depositional and structural framework of the **sedimentary column** (see Table V.A.1) proposed for the injection and confinement of effluent at the TexCom Facility are outlined. Also included is a hydrogeological discussion of the reservoirs in which usable and potentially usable groundwater resources occur. A subsurface prognosis of the formations beneath the TexCom Facility is included (see Table V.A.2). A discussion of hydrocarbon occurrence is presented to describe the state of productive formations in the vicinity of the TexCom Facility.

V.A Regional Geology

The existing injection well and three additional proposed wells will be located within the T. C. Howell Survey, Block A-272, in Montgomery County, Texas. The TexCom **WDW-315** is located on the Gulf Coastal Plain in Southeastern Texas, in Montgomery County. As part of the

coastal plain, it is the site of **regional south dip and southerly thickening** of the Tertiary sedimentary wedge into the Gulf of Mexico. Sediments range from Quaternary to Early Tertiary and Cretaceous and even Jurassic age at great depths. Regional dip into the Gulf is, however, occasionally broken by **local, often salt-cored features**. Jurassic sediments include great thicknesses of salt left behind during periods of evaporating sea water. This deeply buried salt becomes upwardly-mobile in some areas of the Gulf of Mexico Basin and moves toward the surface, **deforming overlying sediments**. One area with numerous salt structures is the Houston Salt Basin that is home to a number of small and large salt piercement features (USGS, 1995). The Conroe Oil Field is located on one such a salt-cored feature – **the Conroe Dome – a large, nearly circular, faulted structure**. The north flank of the Conroe Dome includes the WDW-315 well and the adjacent injection reservoir. The Conroe field is set up by a large domal structure that culminates approximately 2.7 miles to the south of the injection facility. A part of the large Conroe structure is the **E-W, down-to-the-basin fault** shown on the maps in this section **approximately 7,300 feet south of the WDW-315 injection well**. This and similar faults set up the oil production within the prolific Cockfield Formation at the giant Conroe Field.

V.A.1 Regional Petroleum Production

Oil in the Cockfield sands in the Conroe Oil Field was **discovered in 1931**. This giant field has produced more than 717 Million bbls of oil through 1993. The Conroe oilfield includes approximately **17,000 acres** and has seen approximately **750 producing wells** within its boundaries. Many of these wells have been plugged and abandoned; **the area around the WDW-315 injection well includes many plugged producing wells**. **The majority of the hydrocarbons have produced from the Cockfield sands at approximately 5,000 feet in depth**. Deep production from Wilcox sands also occurs in parts of the Conroe Field. **Wilcox production can extend below 14,000 feet below the surface**. Parts of the Conroe field **also have oil and gas production from shallow sands** draped over the dome; these include the following:

- Pliocene natural gas reservoirs
- Miocene natural gas reservoirs
- Frio natural gas reservoirs
- Vicksburg oil and natural gas reservoirs

Scattered natural gas and oil production occurred in these thin, shallow sands **between the base of usable water (approximately 1,500 feet) and the top of the Jackson Formation (approximately 4,000 feet)** (Exxon-Mobil, 2002). These hydrocarbons make picking the exact base of USDWs difficult at Conroe. This issue of the extent of fresh water is discussed in more detail in the USDW Section.

V.A.2 Regional Stratigraphy

Regional stratigraphy is dominated by Cretaceous and Tertiary infill of the actively subsiding Gulf of Mexico Basin. Subsidence began after initial rifting of the basin in the Early and Middle Jurassic time. During rifting, circulation of sea water was periodically cutoff, giving rise to isolated evaporating basin; this led to the accumulation of **thousands of feet of salt** in the Louann Formation. After rifting ended in the Late Jurassic, marine sediments have accumulated in the Texas portion of the Gulf through the Quaternary. Total thickness of the Mesozoic and Tertiary may reach 45,000 feet (Gore, 1992). The Mesozoic and Tertiary sediments have gradually filled the Gulf Basin in response to global and local sea level changes and sediment in-flow. Locally, the deep, thick Jurassic **salt was able to move up fault planes or other zones of weakness** to form salt-cored, piercement structures that sometimes trapped hydrocarbons. Tertiary sediments have the greatest economic interest because they contain important quantities of oil and gas **and drinkable water**; in addition the Tertiary is reachable by modern drilling methods over most of the basin.

The TexCom disposal project is located in the north central portion of the Gulf Coast Basin and contained within the Tertiary and Quaternary sedimentary section. **Figure V.A.2.a** illustrates the Quaternary and Tertiary stratigraphic column in the northwestern portion of the Gulf Coast (USGS, 1995). **Table V.A.2** lists the formations seen in the borehole of the WDW-315 well. The following discussion focuses only on the strata relevant to UIC permit application – the Yegua through Pleistocene – rather than include the many formations present below that sequence. The Yegua through Pleistocene includes the Upper and Lower Confining Units, the Injection Zone, and the USDWs in the area. The thick sedimentary section below the Yegua should have no effect on the performance of the TexCom injection project.

FIGURE V.A.1: STRATIGRAPHIC COLUMN OF QUATERNARY AND TERTIARY STRATA IN THE NORTHWESTERN GULF COAST

Northwestern Gulf Coast		
QUAT.	Pleistocene	Gulf Coast Aquifer System
	Pliocene	
TERTIARY	Miocene	
	Oligocene	Frio/Anahuac
		Vicksburg
	Eocene	Jackson
		Yegua
		Cook Mountain
		Sparta
		Weches
		Queen City
		Reklaw
		Wilcox
	Paleocene	Midway

Table V.A.2: Subsurface Geology/Stratigraphic Column in the Area of the WDW-315 Well

Formation	Approximate Depth (top)	Approximate Thickness (In WDW-WDW-315)	Remarks
Gulf Coast Aquifer System	Surface	1,525 feet	Porous sands and interbedded mudstone aquitards
Frio/Vicksburg Catahoula Aquifer	1,525 feet	2,563 feet	Mudstones with interbedded sand aquifers
Jackson Formation	4,088 feet not drilled	1,046 feet	Upper Confining Zone, massive marine mudstone
Yegua/Cockfield Formation	5,134 feet	Not Fully Penetrated	Includes Injection Zone sands and Lower Confining Zone shale

V.A.2.a Yegua/Cockfield Formation

The Middle Eocene Yegua Formation is a sequence of fluvial, deltaic, and shelf sediments including sands and massive mudstones. Sands are often very high quality reservoirs with porosities in excess of 37% and permeabilities over 2,000 md (USGS, 1995). These sands are frequently productive of hydrocarbons in structural traps arrayed in several coast-wise bands. Productive depths increase from onshore toward the center of the basin and range from 1,000 feet to over 10,000 feet in the Northwest Gulf. Traps are set up by growth faults pene-contemporaneous with the deposition of the Yegua or in various salt-cored structures. Locally the Yegua contains other named members including the Cockfield Formation, which includes the Injection Zone in the current injection application.

V.A.2.b Jackson Formation

The Upper Eocene Jackson Formation consists of shelf sands interspersed with thick marine shelf and upper slope mudstones. Regionally sands are present as scattered small delta systems with sands approaching 30% porosity and 800 md permeability; overall sand content varies from absent to minor. Productive depths range from 500 feet to 6,000 feet in the Northwest Gulf. Hydrocarbon traps are both structural and stratigraphic in nature.

V.A.2.c Frio/Vicksburg

Oligocene sediments are present across the northwest portion of the Gulf Coast as the Frio and underlying Vicksburg Formations. The Vicksburg in the up-dip portion of the basin is composed of fluvial sands scattered in a mudstone sequence. These sands are occasionally thick enough to form oil and gas reservoirs of moderate quality with porosities approaching 30% at productive depths between approximately 4,000 and 11,000 feet (USGS, 1995). The Frio in the up-dip and mid-dip portions of the basin consists of high quality deltaic and strandplain sands often over 35% porosity and permeabilities up to 3,500 md. The Oligocene is also present in the up-dip portion of the basin as the Catahoula aquifer carrying fresh or brackish water in the upper sands more or less equivalent to the Frio Formation.

V.A.2.d Gulf Coast Aquifer System

In the up-dip part of the Northwest Gulf Basin, the Miocene, Pliocene, and Pleistocene are present as high quality fluvial, deltaic, and coastal plain sands with porosities over 35% and permeabilities of 1,800 md at depths ranging from 1,000 to 12,000 feet (USGS, 1995). Some hydrocarbons are produced from this sequence in up-dip structural traps but most importantly the

sands are frequently filled with fresh water resources. Local names differ but in the up-dip part of the northwestern Gulf Coast, the common name for the fresh water bearing sequence is the Gulf Coast Aquifer System (GCAS).

V.A.2 Regional Hydro-Stratigraphy

Major freshwater aquifers in the Northwest Gulf Coast Basin in south-east Texas are combined into the GCAS, a series of fluvial sands with occasional mudstone aquitards that is present across the Texas coastal plain as an arcuate wedge pinching out to the north of the study area and thickening into the Gulf of Mexico. In addition, the Frio/Vicksburg formations in their extreme up-dip positions also can contain fresh water resources. These two aquifers can combine to form a thickness approaching 4,000 feet of water-bearing section to supply water needs in the area (Kasmerak and Robinson, 2004). The strata are summarized as follows:

The GCAS is a thick sequence of fluvial sediments draped over the Tertiary Gulf Coast Plain. In its up-dip position the sands are filled with fresh water while in the down-dip areas the porosity can contain salt water and hydrocarbons. In the up-dip position, sands are often high quality and easily reached by drilled water wells that serve both domestic and municipal systems.

The Catahoula Formation contains variable amounts of sand in an up-dip shelf sequence approximately equivalent to the Frio and Vicksburg Formations. In the Northwest Gulf Coast Basin, the Catahoula can contain fresh or brackish water or hydrocarbons. Hydrocarbons, if present, will be isolated in structural traps most likely located over salt-cored structures.

Freshwater recharge to the aquifer systems described above primarily comes from rainfall on the wide-spread outcrop areas. The average annual precipitation on the aquifer outcrop band is about 50 inches. Surface-water seepage from lakes and streams on the outcrop is also a source of ground water. Water in the outcrop area is unconfined and under water-table conditions but down-dip from the outcrop, the aquifers are confined under hydrostatic pressure and the water is largely under artesian conditions. All the aquifers are unconsolidated sands prone to compaction and subsidence as groundwater is withdrawn. In the vicinity of the TexCom facility, the base of USDWs (that is, the base of groundwater less than 10,000 ppm Total Dissolved Solids) varies but is no deeper than the base of the Catahoula aquifer at approximately 4,000 feet beneath the surface.

V.A.3 Definition and Description of Confining Zone and Injection Zone

In this permit application, geological definitions for the confining zone and the injection zone have been designated in terms of stratigraphy and wire-line log parameters. Major elements are listed in Table V.A.3.1.

The Cockfield Formation contains the lower confining zone and the injection zone; the Cockfield consists of a thick marine mudstone section overlain by interbedded sands and mudstones. The Lower Confining Zone is the Cockfield Shale Member, lowest of four members of the formation and consists of massive marine mudstone. The Lower, Middle, and Upper Cockfield Sand Members form the Injection Zone; these sand packages are interspersed with scattered mudstones. **The Lower and Middle Cockfield Sand Members form the Injection Interval.** The Jackson Formation, approximately 1000 feet of marine mudstone, forms the Upper Confining Zone.

TABLE V.A.3.1
Injection Elements in the Area of the WDW-315 Well

Element	Formation	Approximate Depth (top)	Approximate Thickness	Remarks
Upper Confining Zone	Jackson	4,088 feet	1,046 feet	Massive marine mudstones
Injection Zone	Upper, Middle, and Lower Cockfield Sands	5,134 feet	1,256 feet	Sand aquifers with interbedded mudstones
Lower Confining Zone	Cockfield Shale	6,390 feet (not fully penetrated)	1,500 feet	Massive marine mudstone

V.A.4 Regional Cross-Section

Published dip-wise and strike-wise regional structural cross-sections (Figures V.B.4.1 and V.B.4.2) are included in this permit application and discussed below. The cross-sections illustrate the continuity of the large stratigraphic units; in particular the persistence of the Jackson Formation, the upper sandy portion of the Cockfield, and the lower Shale Member of the Cockfield. While individual sands within the Cockfield show less continuity, the sand-filled interval remains fairly consistent. **The attitude and character of the individual Cockfield sands within the AOR will be discussed in a later section.**

V.A.5 Regional Structural Geology

The Northwest Gulf Coast is a south-dipping, south-thickening wedge of Mesozoic and Tertiary sediments that have progressively filled the actively subsiding basin. The combination of continuous sedimentation along with subsiding basin has left more or less continuous, regional dip into the basin. Subsidence has mobilized the thick salts in the Jurassic and caused them to

move into local thickenings and [to pierce the overlying strata](#), giving rise to local counter-regional structures. Faulting in this part of the basin is both regional, shore-wise down-to-the-basin faults caused by basement discontinuities as well as localized down and up-to-the-basin faults caused by salt movement, isolated sediment loading at depo-centers, and local basement anomalies.

V.A.6 Regional Seismic Activity

The closest earthquake occurred on 8 May 1910 near Hempstead, Texas, about 70 km northwest of Houston. This earthquake had a magnitude of about 3.8, and was felt by individuals within about 30 km of Hempstead, but not in Houston. Of course, Houston residents in tall buildings may occasionally feel large, very distant earthquakes that occur in western Texas or even Mexico.

Near Houston there may be examples of faults which are active, but which don't have any earthquakes. Land in some communities southeast of Houston such as Clear Lake and Dickenson is sinking because water has been pumped out from the ground for many years; this sinking may be associated with slip along faults. However, when such slip is a slow or continuous "creep," it isn't an earthquake. To cause an earthquake the faults need to "stick" then slip suddenly enough to radiate seismic waves (UT, 2005).

V.A.6.a Induced Seismicity

Fluid-injection induced earthquakes are most likely caused by the increased pore pressure from injection operations that have reduced frictional resistance to failure. This mechanism has been used to explain the best known case of injection-induced seismicity, which occurred at the Rocky Mountain Arsenal near Denver, Colorado. In Texas, there are at least two known examples of previously seismically inactive areas becoming seismically active after major injection programs began. One site is located in the Central Basin Platform, near Kermit, and the other is in the Midland Basin, near Snyder. In both cases, large-scale, high-pressure, oil-field related water-flooding projects were underway, and [earthquakes with magnitudes of over 4.0 on the Richter Scale were recorded](#). No induced earthquakes have been known or are postulated to have been caused by the relatively low-volume, low-pressure Class I injection operations, such as those anticipated at the TexCom Facility (Davis, 1989).

V.A.6.b Seismic Risk

Faults within the Northwest Gulf Coast Basin are predominantly the result of localized structural adjustments and are not linked into regional fault systems such as the San Andreas or Rough

Creek fault systems. Movement along these laterally small faults was driven by sedimentary loading and was greatest when the area was receiving the largest sediment load during the Eocene. Since that time, sediment loading has decreased as the inner shelf sedimentation band has shifted basinward. Fault movement has, therefore, decreased since the Eocene and the chance for sudden slip on the faults and the resultant earthquakes is quite slim.

A seismic risk map, based on past seismic events in the region, places the TexCom Facility in a risk zone of 0. This risk factor has been assigned to the region based on: 1) distribution of maximum Modified Mercalli intensities associated with the known seismic history of the United States; 2) [strain release](#) in the United States since 1900; 3) the association of strain release patterns with large-scale geologic features believed to be related to recent seismic activity. The risk factor of 0 assigned to the region corresponds to maximum measured and predicted intensities of V to VII on the Modified Mercalli scale. By definition, earthquakes of this magnitude would do little structural damage.

Table V.A.6.b: Earthquake Hazard Data (USGS, 2005)

ZIP CODE	77303		
LOCATION	30.3605 Lat. -95.4146 Long.		
DISTANCE TO NEAREST GRID POINT	4.5982 kms		
NEAREST GRID POINT	30.4 Lat. -95.4 Long.		
Probabilistic ground motion values, in %g, at the Nearest Grid point are:			
	10%PE in 50 yr	5%PE in 50 yr	2%PE in 50 yr
PGA	1.394491	2.511504	4.880487
0.2 sec SA	3.374499	5.645645	11.079900
0.3 sec SA	2.907931	5.034945	9.110430
1.0 sec SA	1.246442	2.502708	4.882367

Based on historical data and the geologic setting (absence of faults in the immediate plant vicinity), the probability of a seismic event occurring with the magnitude to damage the injection strata or facilities is extremely remote at the TexCom Facility.

V.A.5 Regional Groundwater Flow in the Injection Zone

Groundwater is contained in the GCAS in the region of the Northwest Gulf Coast. As discussed above, water enters the GCAS at the outcrop band just north of the TexCom Facility either by way of precipitation or infiltration from lakes, ponds, and streams over the outcrop. Upon entering the aquifer system, water migrates down-dip (south) to replenish depleted reservoirs and to enter deeper aquifers within the thick, widespread GCAS. Localized depletion of aquifers can cause local changes in the down-dip gradient and can cause groundwater to flow in a cross-dip or even up-dip direction in response to pressure gradients.

V.B Local Geology

The TexCom Facility is located in Montgomery County, Texas within the Northwest Gulf Coast Basin at the up-dip edge of the Houston Salt Basin. The basinward-thickening wedge of Mesozoic, Tertiary, and Quaternary sediments with associated, isolated faulting and salt-cored structures dominate the regional geology as well as the geology within the TexCom Area of Review (AOR). The sediments in the Gulf Coast Basin wedge range in age from Jurassic to Recent as well as across the AOR but the most important strata in terms of the TexCom UIC permit application are those of Upper Eocene to Quaternary.

V.B.1 Local Stratigraphy

Local strata will be discussed in as they appear in the AOR of the subject injection well and close-by surrounding wells. Figure V.B.1.1 is a stratigraphic column of the WDW-315 that illustrates the sedimentary section within the AOR of the UIC application. More attention will be shown to the injection zone and confining zones as shown in Figure V.B.1.2, the stratigraphy and regulatory units of the Jackson and Cockfield Formations in the WDW-315 well and in the AOR. Figure V.B.1.3 is the wire-line log through the members of the Cockfield Formation in the WDW-315 well. Table V.B.1.1. is the Local Stratigraphic Column for the AOR.

Figure V.B.1.1: Stratigraphic Column for the WDW-315 Injection Well, Montgomery County, Texas

Stratigraphy: TexCom WDW #315		
Quaternary	Pleist.	Chicot Formation (0' to 150' MD)
	Plio.	Evangeline Aquifer (150' to 715')
	Mio.	Burkeville Confining Unit (715' to 1010')
		Jasper/Oakville Aquifer (1010' to 1525')
	Oligo.	Frio/Vicksburg/ Catahoula (1525' to 4088')
	Eocene (part)	Jackson Formation (4088' to 5134')
		Yegua/Cockfield Formation (5134' to TD) (Not Fully Penetrated)

Base of USDW
(4088')

Injection Zone

Stratigraphy of USDWs

The strata above the Jackson Formation are a sequence of freshwater to brackish water-bearing units that are described in the Hydro-Stratigraphy Section following.

V.B.1.a Jackson Formation – Upper Confining Zone

The massive marine mudstones of the Jackson Formation form the Upper Confining Zone of the WDW-315. Both the upper and lower contacts of the Jackson are sharp discontinuities with overlying and underlying sands. The Eocene age mudstones have only a few, very thin sand interbeds within the 1092-foot section at WDW-315 well; the aggregate sand content is less than 50 feet of widely separated, thin sands. These sands, likely distal shelf sand bodies, may have some porosity and permeability but are clearly unconnected. Moveable water content within the total Jackson section will be minor and water quality is unknown; water content will likely be a combination of original marine pore-water and nearly fresh water-of-crystallization expressed out of the clay mineral lattice during maturation and induration.

The Jackson Formation makes an excellent Upper Confining Unit that will prevent upward migration of injectate into overlying USDWs. This thick, marine mudstone will effectively seal the 100-foot to 150-foot fault that is present approximately 7,300 feet south of the well and it will seal any smaller, unknown faults that may occur in the Tertiary sequence.

In the North Conroe Area, the Jackson is a consistently massive mudstone varying from 853 feet to 1,144 feet in thickness. Figure V.B.1.4 is the isopach map of the Jackson Formation; little variation is displayed however it is apparent that the Conroe Dome was a positive feature during the deposition of the Jackson so that the formation thins over the dome. It appears that well C-233 is anomalously thin in the Jackson and may have cut a normal fault of approximately 150 feet of throw; whether or not this is the fault mapped on field maps such as Michaux and Buck, 1936 (Figure V.B.1.6 discussed below) is unknown. The lack of internal character on wireline logs make correlations within the Jackson difficult and suggests that sands are thin and discontinuous.

Figure V.B.1.5 is the structure map on the top of the Jackson. This log marker contains the best control from modern wire-line logs. The structure in this map can be seen to be parallel to the earlier, better-controlled structure mapped in Figure V.B.1.6 discussed below. The East-West fault is evident in the structure map but lack of close well-control limits precise positioning of the fault. The fault trace would be expected to dip south at a moderate angle, making the trace at the Jackson level approximately one-quarter of a mile north of the trace at the Upper Cockfield level but this cannot be demonstrated.

V.B.1.b Yegua/Cockfield Formation

The Middle Eocene Cockfield Formation in the area of WDW-315 and Conroe Field is stratigraphically equivalent to the Yegua Formation of the deep regional subsurface. This formation of approximately 3000 feet of sand and shale forms a major oil reservoir in the Northwest portion of the Gulf of Mexico basin; the Conroe Field has produced more than 717 Million Bbls of oil from the Cockfield. The Cockfield Formation itself can be broken down into four stratigraphic members as diagrammed in Figure V.B.1.2. The Upper, Middle, and Lower Sand Members combine to form the Injection Zone at the WDW-315 well while the well is perforated in the Lower and Middle Sand Members. The basal Shale Member, not fully penetrated in the WDW-315 well, makes up the Lower Confining Unit at the TexCom Facility. Figure V.B.1.3 is the wire-line log character of the members of the Cockfield in the WDW-315 well.

Figure V.B.1.2: Cockfield Formation in the WDW-315 Well; Illustrated with Open-Hole Wire-Line Logs.

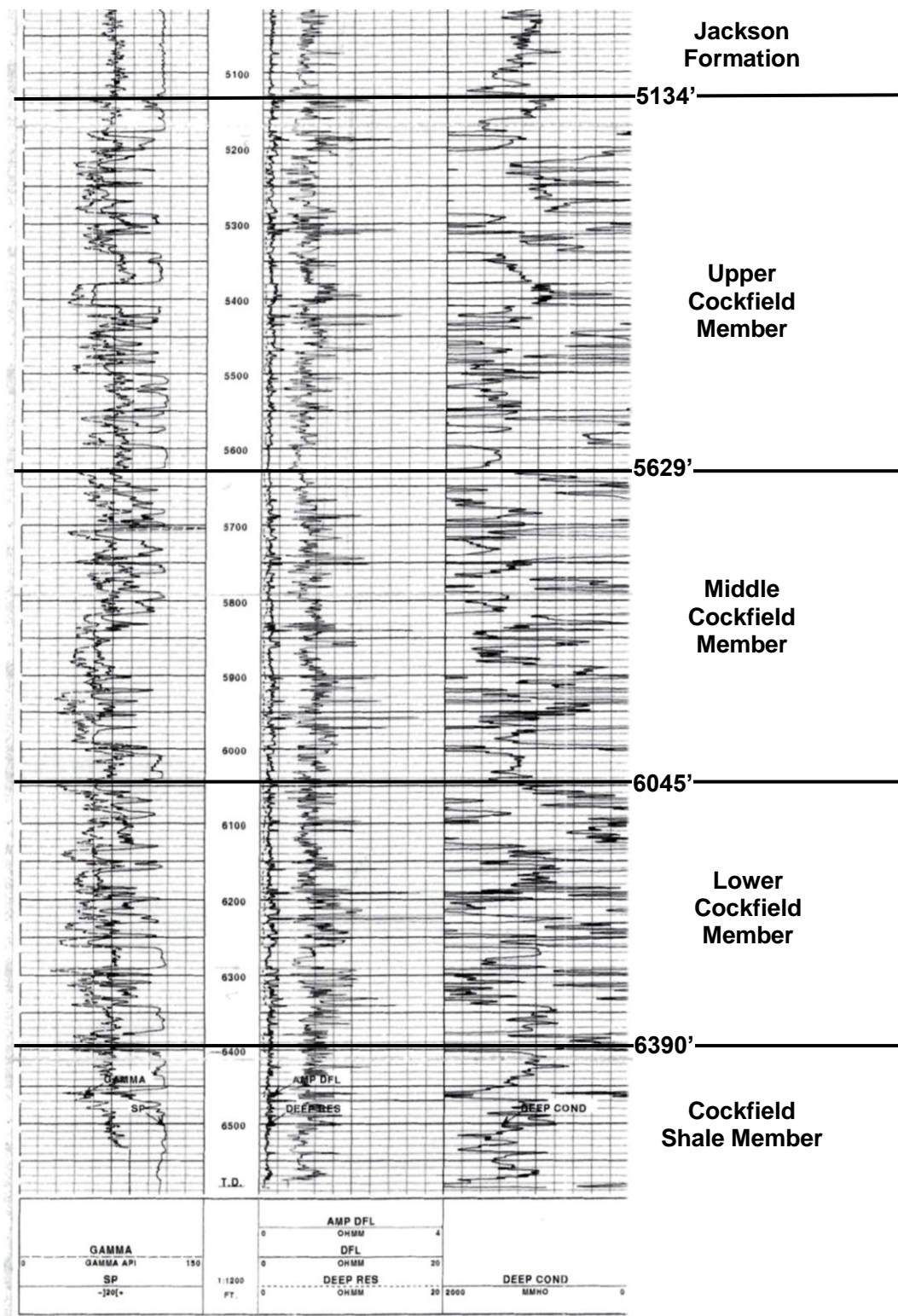


Figure V.B.1.3: Important Regulatory Units in the AOR.

Strat Column: TexCom WDW #315			
Eocene (Part)	Jackson Formation (4088' to 5134')		Upper Confining Zone 5134'
	Cockfield Formation (5134' to TD) (NFP)	Upper Cockfield Member	Injection Zone
		5629'	
		Middle Cockfield Member	
		6045'	
		Lower Cockfield Member	6390'
	Cockfield Shale Member (6390' to TD')		Lower Confining Zone

V.B.1.b.i Upper Cockfield Member

The Upper Cockfield Member is predominantly sand with two main shale interbeds and numerous thin shale partings. The Upper Cockfield Member is the reservoir that has historically produced oil at the Conroe Field; the included sands are of very high quality with porosities in excess of 30%. Progradational, deltaic sands are rare in the Upper Cockfield; most of the sands are rather thick, consistent packages of regression, shoreface sands separated by thin, transgressive marine shales. Thicker individual shales up to 42 feet in thickness separate the sand packages. There is a total of 188 feet of clean sands in the Upper Cockfield with the thickest individual sand being 29 feet thick in the WDW-315 well. Sands appear to range from 27% to 35% but average approximately 32%. Porosities are highest in this Upper Member of the Cockfield, perhaps due to the effects of the reservoir hydrocarbons protecting the rock frame from diagenetic porosity plugging. The upper contact of the Member is a sharp discontinuity between the massive Jackson Formation and an uppermost seven-foot thick sand. The lower contact exists at the base of a particularly persistent 32-foot shale that sits on top of the deltaic sands of the Middle Cockfield unit.

The Upper Cockfield in the North Conroe Area is remarkably consistent as is appropriate for a marine sand package. Sand and shale units are persistent and [easily correlatable across the Area of Review](#) (AOR). The total thickness of the member varies from 423 feet to 495 feet. Structure on the highest correlative sand in the Upper Member across the AOR is shown in Figure V.B.1.6 (Michaux and Buck, 1936). This published map of the Conroe field was constructed from drillers' data that no longer exists; most of this drilling took place prior to the widespread use of wireline logs. This map is, therefore the best one available to illustrate the structure of the Conroe Dome and across the AOR; other maps that accompany this application are based on the [scattered wire-line log data](#) that currently exists. This map clearly shows the position of the E – W fault to the south of the WDW-315 well. [At the Upper Cockfield level, the fault shows approximately 100 to 150 feet of throw](#). Near the disposal well, on the north flank of the Conroe Dome and north of the E – W fault, dip is to the north until it encounters regional south dip and reverses. Dip changes from approximately 200 feet/mile at the edges of the dome to nearly flat at the apex of the dome in the southern portion of the AOR. Figure V.B.1.7 is the structure map [on the top of the Upper Cockfield Member](#) constructed from modern wire-line log data; the map illustrates a structure setting similar to the older map in Figure V.B.1.6 but with considerably less subsurface data.

V.B.1.b.ii Middle Cockfield Member

Within the WDW-315 well, the Middle Member consists of 662 feet of largely progradational, deltaic sands separated by somewhat thick, persistent shales. The Middle Member, in the vicinity of the WDW-315 well and in the AOR, [is always below the original oil/water contact and therefore was not productive of hydrocarbons](#). Sands range up to 49 feet thick while porosities range up to 33% but average approximately 29%. Upper contact is the discontinuity between the basal shale of the Upper Member with [a massive deltaic sand](#). The lower contact is the discontinuity between a persistent 27-foot shale at the base of the Middle member and the first of a series of finely-bedded sands and shales at the top of the Lower member. [The Upper, Middle, and Lower Cockfield Members make up the Injection Zone of the WDW-315 well](#). Because no thick shales divide the Lower or Middle members, the two are likely connected across the 100 to 150-foot fault to the south of the well.

The **Middle Cockfield** member shows more variation than the Upper Cockfield. Deltaic sands in the Middle unit [do not correlate well between boreholes](#) suggesting that depo-centers are connected to small rivers feeding small delta systems. Thickness of the member varies from [607 feet to 662 feet](#). The structure on the top of the Middle Member is expected to be parallel with the structure shown in Figure V.B.1.6, the structure on the top of the Upper Member.

V.B.1.b.iii Lower Cockfield Member

The Lower Cockfield Member is present in the WDW-315 well as 111 feet of shales and thin sands. The sands appear to be thin pro-delta extensions of deltaic packages being deposited up-dip to the north. The sands are uniformly lower quality than those sands in the Upper and Middle Members with porosities ranging up to 29% but averaging approximately 22%. Sands are mostly thinly bedded with shale interbeds; the thickest sand appears to be seven feet thick while most are thinner. The upper contact of the Lower Cockfield is the lower boundary of a persistent shale at the base of the Middle member. The lower contact is the base of the last persistent sand within the Lower member. **The Lower Cockfield Member sands are the only sands perforated in the WDW-315 well and therefore make up the Injection Interval.** The Upper, Middle, and Lower Cockfield make up the Injection Zone of the WDW-315 well. Because no thick shales divide the Lower or Middle members, the two are likely connected across the 100 to 150-foot fault to the south of the well.

The Lower Cockfield marine sands **correlate very well between boreholes** while thickness of the member varies from 111 to 156 feet.

V.B.1.b.iii Cockfield Shale Member – The Lower Confining Zone

The lowest unit of the Cockfield is the Cockfield Shale Member. In the WDW-315 well, only 182 feet of this thick shale was penetrated and total thickness at that location is, therefore, unknown. The unit consists of massive marine shale with few thin sands and tite siltstones; only two feet of porous sands appear to be present in the WDW-315 well. The Cockfield Shale forms the Lower Confining Unit for the WDW-315 injection system. Structure on the top of the shale member is shown in Figure V.B.1.8. This map parallels the structure on the top of the Upper Cockfield Sand Member in the presence of the East-West fault and the Conroe Dome. In the North Conroe area and in the AOR, only two boreholes fully penetrated the entire Cockfield Shale section; these wells encountered 1425 feet and 1639 feet of shale and are shown on Figure V.B.1.9, which suggests that the Conroe Dome was active during the deposition of the Cockfield Shale Member with thinning on top of the structure. The thickness of this shale package is much thicker than the fault to the south and so will seal this fault to any migration of injected fluids. With the confining action of the massive Jackson mudstone and Cockfield Shale Member, the injectate entering the Cockfield sands will be confined by massive marine mudstones and shales from above and below.

Table V.B.1.4: Local Stratigraphic Column

Local Stratigraphic Column TexCom Facility, Montgomery County, Texas				
SYSTEM	STAGE	GROUP or FORMATION		Regulatory/Hydrostratigraphic Unit
Quaternary	Pleistocene	Gulf Coast Aquifer System		Aquifers
Tertiary (Part)	Pliocene			
	Miocene			
	Oligocene	Catahoula Formation (Frio/Vicksburg)		Buffer and Aquiclude Base of Lowermost USDW
	Eocene (Part)	Jackson Formation		Upper Confining Zone
		Cockfield Formation	Upper Member	Injection Zone
			Middle Member	
			Lower Member	
			Shale Member	Lower Confining Zone

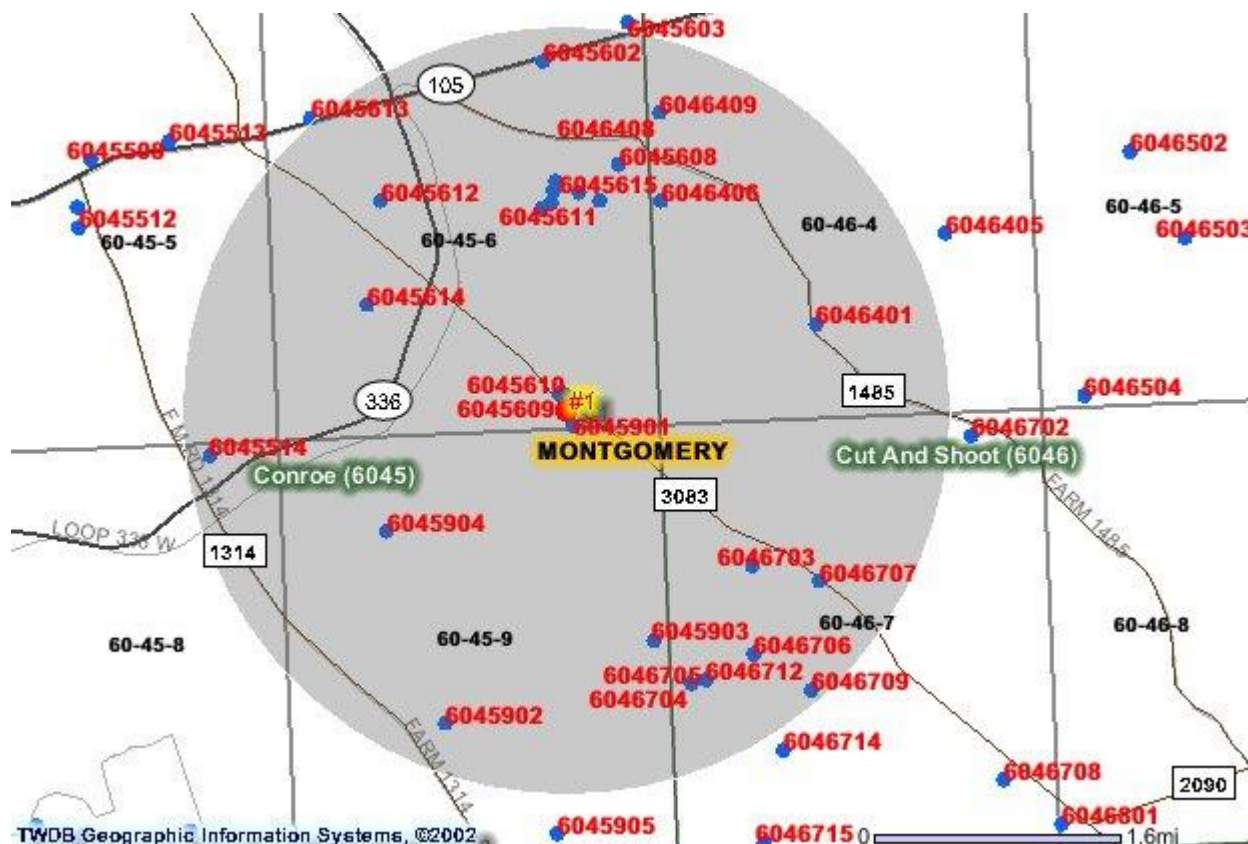
V.B.2 Local Hydro-Stratigraphy

Local ground water stratigraphy is illustrated in Figure V.B.2.1 and depths of the hydrological elements in the TexCom WDW-315 well. The hydro-stratigraphy of the USDWs is dominated by the GCAS, approximately 1525 feet of sand-rich sediments of Pleistocene through Miocene age. Figure V.B.2.2 is a map of the AOR with locations and State ID numbers for 26 water wells within the AOR (TWDB, 2005). Of the 26 wells, three wells are completed in the Chicot aquifers from depths 100 feet or less. Nineteen wells are completed in the Evangeline Aquifer at depths ranging from 123 feet to 735 feet deep. Four are completed in the Jasper aquifer between 1100 and 1500 feet deep. One well, completed at 5500 feet of depth is listed as a water well; drilled by Humble Oil, this well is most likely a water flood supply well producing unpotable saltwater. While shallow aquifers can supply domestic water wells, municipal supply is largely derived from Evangeline or Jasper aquifers. The Texas Water Development Board lists no drinking water wells drilled below 1500 feet within the AOR.

Figure V.B.2.1
Local Hydro-Stratigraphy at TexCom Injection Facility

Hydrological Strat Column: TexCom WDW #315				
Tertiary	Quat.	Pleist.	Chicot Aquifer (0' to 150' MD)	
	Miocene	Gulf Coast Aquifer	Evangeline Aquifer (150' to 715')	
			Burkeville Confining Unit (715' to 1010')	
			Jasper – Oakville Aquifer (1010' to 1525')	
	Oligo.		Catahoula Confining Unit (1525' to 4088')	
			Minimum Surf. Csg. (TCEQ): 1550'	
			Base of USDW (4088')	

Figure V.B.2.2: Map of TexCom Injection Facility and Water Wells. 2.5-mile Area of Review is shown.



V.B.3 Definition and Description of USDW, Confining Zone, Injection Zone, Injection Interval, and Lower Confining Strata

In this permit application, definitions for the USDW, confining zone, injection zone, injection interval, and lower confining strata have been designated. Each is described in the following paragraphs.

V.B.3.a USDWs

The base of the lowermost USDW is at approximately 4088 feet below surface in the geophysical log at the TexCom WDW-315 well. Figure 4 is a stratigraphic column of the USDWs in the area of the WDW-315 injection well. USDWs consist of two major systems – the GCAS and the underlying, Miocene age Catahoula Aquifer. These two systems are discussed below and cast in a cross-section in Figure V.B.3.1.

V.B.3.a.i Gulf Coast Aquifer System

Outcropping stratigraphic units often have different names in the deep subsurface; this is especially true for important aquifers that become hydrocarbon bearing as they move down-dip into the deep subsurface. Aquifers are named from their outcropping recharge areas but are the stratigraphic equivalents of oil-bearing formations developed in the deep basin. From the land surface downward, the Chicot aquifer, the Evangeline aquifer, the Burkeville confining unit, and the Jasper-Oakville aquifer are the hydrogeologic units of the Gulf Coast Aquifer System (GCAS), as described by (Baker, 1979 and 1986) and (Ashworth and Hopkins, 1995). The Chicot aquifer comprises (youngest to oldest) the alluvium, Beaumont Clay, Montgomery Formation, Bentley Formation, and Willis Sand. The Evangeline aquifer comprises (youngest to oldest) the Goliad Sand and the upper part of the Fleming Formation. The Burkeville confining unit consists of the middle portion of the Fleming Formation. The Jasper aquifer comprises (youngest to oldest) the lower part of the Fleming Formation throughout its subsurface extent and the uppermost part of the Catahoula Sandstone in its outcrop and extreme updip parts. The basal contact of the GCAS is the Catahoula confining unit, which comprises the Catahoula Sandstone, and the downdip Frio and Vicksburg Formations (Kasmerak and Robinson, 2004).

The paleo-depositional environment of the rocks that formed the GCAS was a fluvial deltaic or shallow-marine environment that produced inter-layered, discontinuous sequences of sand, silt, clay, and gravel. Changes in land-surface altitudes related to naturally occurring land surface subsidence of the depositional basin and sea-level transgressions and regressions created cyclical sedimentation facies. During periods when the sea level declined, fluvial deltaic processes deposited continental sediments; but as the sea level rose, the deposited continental sediments were reworked and marine sediments were deposited. Because of this complex depositional process, the facies alternate cyclically from the predominantly continental sediments that compose the aquifers to the predominantly marine sediments that compose the confining units and clay layers within aquifers. Therefore, the aquifer system has a high degree of heterogeneity in both lateral and vertical extent (Sellards and others, 1932).

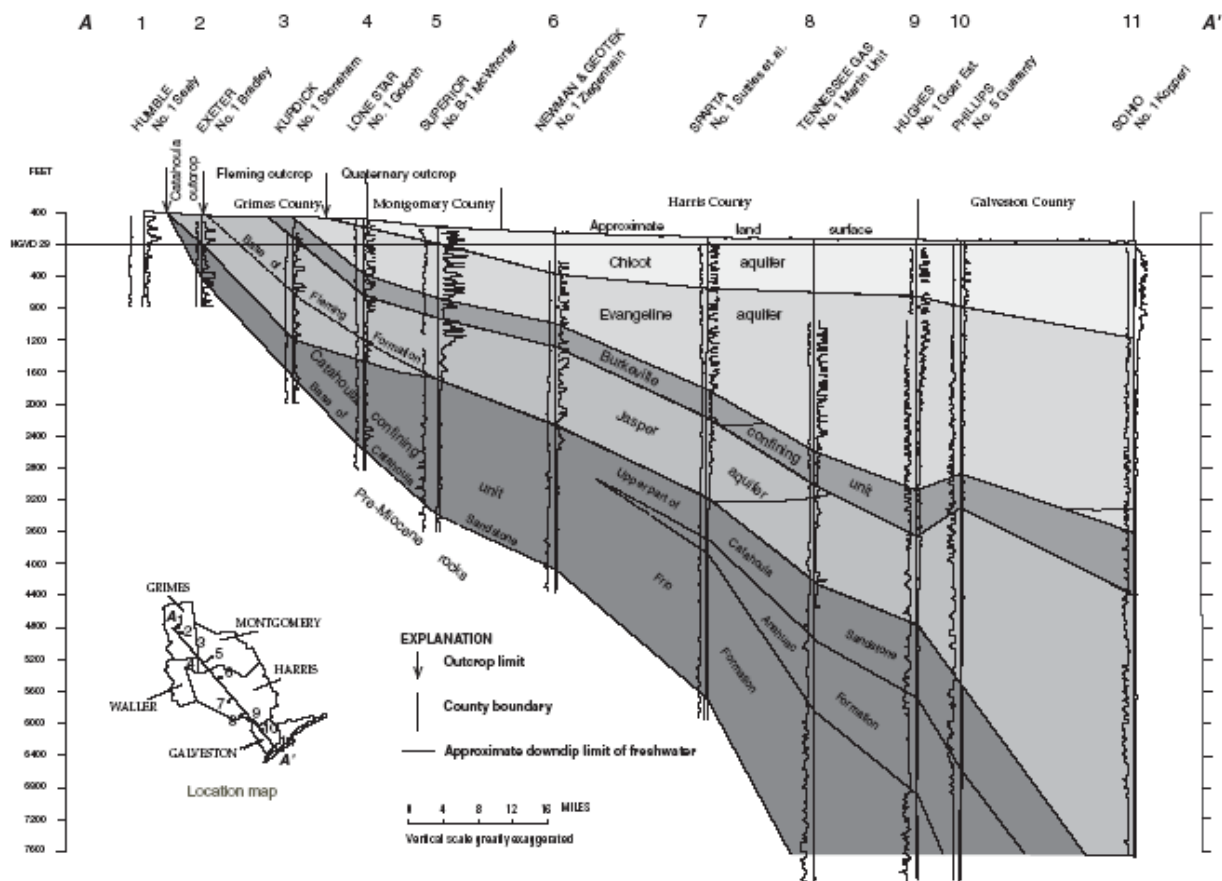
Figure V.B.3.1 illustrates the structural cross-section of the USDWs in the Galveston-Houston-Conroe area (Kasmerak and Robinson, 2004). This cross-section crosses Montgomery County and proceeds basinward to the Gulf. In so doing, the cross-section encounters the elements of the USDWs in the geological column. The USDWs are also present within the WDW-315 well as described below:

- The Chicot Aquifer varies in thickness in Montgomery County between 0 and approximately 400 feet as it thickens into the Gulf of Mexico; in the county it is predominantly fluvial sand (Kasmerak and Robinson, 2004). The cross-section in Figure

V.B.3.1 reports approximately 200 feet of Chicot Aquifer in Montgomery County (Kasmerak and Robinson, 2004). At the WDW-315, the Chicot is approximately 150 feet thick but lithology is unknown.

- The Evangeline Aquifer varies between 0 and 1000 feet in thickness across Montgomery County; lithology is predominantly sand (Kasmerak and Robinson, 2004). Figure V.B.3.1 reports some 700 feet of Evangeline, well above the fresh-to-brackish water transition. At the WDW-315, the Evangeline is 565 feet of interbedded mudstone and sand with two thick sands at its base.
- The Burkeville Confining Unit is a nearly pure, massive mudstone with scattered, very thin limestone laminae. Figure V.B.3.1 reports approximately 300 feet of Burkeville mudstone. In the WDW-315 well, the Burkeville is present as 295 feet of section made up mostly of mudstone. No porous/permeable sands are present on wire-line logs. This unit is clearly an aquitard within the GCAS.
- The Jasper-Oakville aquifer (of Miocene age) is the lowermost of the three primary aquifers of the GCAS. The Jasper-Oakville aquifer is overlain by the Burkeville confining unit (of Miocene age), which in turn is overlain by the Evangeline aquifer (of Miocene and Pliocene age) and the Chicot aquifer (of Pleistocene and Holocene age). These hydro-geologic units dip from the land surface southeastward at slight angles toward the Gulf of Mexico. The units thus crop out in bands approximately parallel to the coast. The Jasper-Oakville aquifer outcrop band, which comprises the oldest sediments, is the farthest inland of the aquifer outcrops. The Jasper-Oakville aquifer in the greater Conroe area thickens toward the coast from about 600 feet in the outcrop to about 1,000 feet. The Jasper-Oakville aquifer can be separated into two parts on the basis of lithology. The upper part, which makes up 50 to 80 percent of the aquifer, consists of a massive sand; the lower part consists mostly of interbedded sand and clay (Coplin and Lanning-Rush, 2002).

Figure V.B.3.1 reports approximately 600 feet of Jasper-Oakville well above the fresh-to-brackish interface (Kasmerak and Robinson, 2004). In the WDW-315, the Jasper-Oakville is approximately 515 feet thick represented by an upper massive sand approximately 210 feet thick overlying a section of interbedded sands and mudstones.

Figure V.B.3.1: Dip-Wise Cross-Section of Gulf Coast Aquifer System (Kasmerak and Robinson, 2004).**V.B.3.a.ii Catahoula Aquifer**

In the region around the Northwest Gulf Coast, the Oligocene is present as the Frio/Vicksburg Formation; these strata are known in the updip position around the WDW-315 well to groundwater workers as the Catahoula Aquifer. The position of the Catahoula is displayed in Figure V.B.3.1 above. The Catahoula Formation in the WDW-315 consists of 2,563 feet of thick to thin mudstones separated by thin, fining-upward marine sands. Sands increase toward the bottom of the unit; at the bottom is a 70-foot shaley, fining-upward sand that rests upon the thick mudstone of Jackson Formation. The Catahoula produces oil and gas in the Conroe field but the presence of hydrocarbons in the vicinity of the WDW-315 well is unknown. Resistivities vary but are mostly quite high in the Catahoula, suggesting that salinities are low; any hydrocarbon effects are, however, unknown. The WDW-315 was drilled without mud-logging efforts through the Catahoula. Work by Exxon-Mobil in the Conroe field finds salinities to range from 2,000 to 8,000 ppm (Exxon-Mobil, 2002). Although salinities appear to be within the limits of a USDW, the Catahoula-Frio-Vicksburg has been used as a disposal zone for oil and gas produced waters and scattered presence of produceable hydrocarbons makes the water in this zone unattractive for

drinking uses. In the area of the WDW-315, the Catahoula acts as a protective buffer zone between the Upper Confining Zone (the Jackson Formation) and the GCAS that does carry useable water ranging from high to low quality. Any upward percolating waters from the Cockfield injection zone may escape the Jackson Formation Confining Zone will be intercepted in the Catahoula Formation and dissipated within the numerous thin sands.

V.B.3.a.iii Water Quality

Water quality has been studied in the vicinity of the Conroe Field in several reports. The Texas Water Board maps water quality across the GCA in Montgomery County between less than 500 ppm and 1000 ppm TDS (TWDB, 1989). Exxon-Mobil analyzed the salinity of the formation water in the shallow sandstones of two wells. Above 1000 feet, the formation water was very fresh with a salinity less than 700-800 ppm. Between 1300 feet and 2,000 feet, the salinity was 800-2,000 ppm, indicative of usable-quality water. The massive Oakville aquifer occurs between about 1,050 feet and 1,350 feet. Between approximately 2,000 feet and the base of the Catahoula interval (4,088 feet), thick sands are rare and the water is increasingly brackish, with a salt content between 2,000 and 10,000 ppm. The sands within the Catahoula are only occasionally thick enough to derive wire-line log parameters for calculating salinities. Sands within the Catahoula do produce hydrocarbons in the area of the Conroe Dome and these fluids may influence salinity calculations and make the water appear to be fresher than it actually is. Water quality in the WDW-315 was calculated from available wire-line log data at several points in the well and tabulated below:

Calculated Salinities from WDW-315 WDW Logs			
Formation	Depth	Rw	TDS
Jasper-Oakville	1330 feet	13.08 Ω m/m	<500 ppm
Catahoula	2735 feet	2.22 Ω m/m	2,400 ppm
Catahoula	3315 feet	0.558 Ω m/m	10,000 ppm

The Catahoula equivalents (Lower Frio and Vicksburg Formations) have been and are still being used for disposal of salt water in the area of Conroe Dome (Exxon-Mobil, 2002). In light of all the above information, it is assumed that the top of 10,000 ppm pore-water is the base of the Catahoula at 4,088 feet in the WDW-315 well but the absence of porous sands in the Catahoula makes picking a base of USDW somewhat unreliable. It may be true that the actual base of USDWs is stratigraphically higher than the base of the Catahoula but this cannot be proven at the present time. Below the Catahoula aquifer, pore-water salinities increase to 35,000 ppm, approximately the same as modern ocean water. Figure V.B.3.2 summarizes water quality values for USDWs in the AOR and in the vicinity of the Conroe Oil Field.

A recent casing requirements letter from the TNRCC (now the TCEQ) indicates that in the opinion of that agency, the base of usable quality water is at 1,550 feet. The interval within the Evangeline Aquifer between 650 feet and 1,550 feet must be isolated from water in and underlying beds. Exxon-Mobil has requested a field rule standardizing the casing program for wells not drilled below the proposed upper consolidated field. The casing programs used in wells on the Conroe Dome have evolved over the years. The more recent Cockfield wells, drilled in the 1980's, have surface casing set through the Jasper-Oakville aquifer, to about 1,600 feet. In 2002, Wapiti Energy, LLC, received a permit to drill to 3,800 feet in this area and produce hydrocarbons from the Jasper-Oakville. It was allowed to set surface casing to 500 feet and cement the production casing back to the surface. Exxon-Mobil requested that a field rule allowing a similar casing program to be used for all wells completed in the proposed upper consolidated field (Exxon-Mobil, 2002).

Figure V.B.3.2: Stratigraphic Summary of Water Quality Data in the TexCom AOR.
Depths shown are log-depths from the WDW-315 well.

USDW Water Quality: Conroe Field, Montgomery County, Texas			
Tertiary	Quat.	Gulf Coast Aquifer	Chicot Aquifer (0' to 150') <i><500 to 800 ppm TDS</i>
	Pleist.		
	Pliocene		Evangeline Aquifer (150' to 715') <i><500 to 800 ppm TDS</i>
	Miocene		Burkeville Confining Unit (715' to 1,010') <i>no sands</i>
	Oligo.	Jasper – Oakville Aquifer (1,010' to 1,525') <i><500 to 2,000 ppm TDS</i>	Catahoula Confining Unit (1,525' to 4,088') <i>2,000 to 10,000 ppm TDS</i> <i>Below the Catahoula, pore water is approximately 35,000 ppm TDS</i>

V.B.3.a.iv Buffer Aquifer(s)

The Catahoula aquifer/impermeable aquitard layers fall between the lowermost used aquifers and the top of the Confining Zone. This 2,563-foot thick unit consists of thin sands and thicker mudstones; the sands contain water of poor quality although all the aquifers appear to be less than 10,000 ppm TDS. No water wells use Catahoula aquifers in the AOR although the water is likely treatable to health and aesthetic standards. In particular, the sands at the base of the Catahoula interval are very near or even rest upon the contact with the Jackson Formation confining zone. The sands of the Catahoula will form an effective buffer to inept upward-moving injectate that might escape past the Jackson Formation Upper Confining Zone.

V.B.3.b Upper Confining Zone

The Jackson Formation forms the Upper Confining Zone for the TexCom injection project in Montgomery County, Texas. This thick marine mudstone constitutes an ideal confining zone to seal any faults, fractures, and joints that might propagate upward from the deep sediments draped over the salt piercement structure. These faults, including the 100 to 150-foot fault running E – W in the south half of the AOR, would be sealed by the mudstones which lack the strength to maintain open channels. No core data for the Jackson in the AOR is restricted to the WDW-315 with a single core at 4,600 feet deep in the Jackson that showed permeabilities at 0.01 md (Crossroads, 1994). These permeabilities reflect the wire-line log signatures described above. The consistent thickness of this massive mudstone suggests it will be an excellent confining zone.

V.B.3.c Injection Zone

The Injection Zone in the subject facility includes the Upper, Middle, and Lower Cockfield Sand Members. These three thick sand packages are separated by persistent shales but the shales appear not to be thick enough to isolate the individual sand members either stratigraphically or across faults in the AOR. Reservoir quality appears to decrease as one moves stratigraphically lower. The Upper Member is the highest porosity package; this is the depleted oil reservoir that has been producing since 1932. The Middle Member contains the most sands but they are not as porous (and likely not as permeable) as the Upper Member. The Lower Member has the least sand and the lowest quality sands in the Cockfield. Reservoir statistics as derived from wire-line logs are summarized below. The Injection Interval (from 6,045 feet to 6,390 feet of depth) includes parts of the Middle (across fault) and Lower Sand Members. The Injection Interval currently comprises a total of 100 feet of perforated reservoir. An additional 45 feet of perforations will be added once approval to inject is received

Figure V.B.3.3: Injection Zone Data for TexCom WDW-315

Injection Zone in the TexCom WDW-315 Well				
Member	Interval	Thickness (feet)	Net sand (feet)	Average Porosity
Upper Sand Member	5,134' to 5,629'	495	168	30%
Middle Sand Member	5,629' to 6,045'	416	256	29%
Lower Sand Member	6,045' to 6,390'	345	146	22%
Total Cockfield Sands	5,134' to 6,390'	1,256	570	29%

V.B.3.d Lower Confining Zone

Injectate is confined into the Cockfield sand Injection Zone from below by the presence of a large thickness of marine shales known locally as the Cockfield Shale Member. This interval was not cored in the WDW-315 well but the shale is approximately the same age as well as the same environment of deposition and appears to be similar in reservoir characteristics to the Eocene Jackson Formation as discussed above.

V.B.4 Local Stratigraphic Cross-Sections

Two cross-sections that cross the AOR have been published. Figure V.B.4.1 is an East-West cross-section supplied by Crossroads for their original Class I UIC application (Crossroads, 1994). Figure V.B.4.2 is a North-South cross-section supplied by Exxon for a TRRC hearing (Exxon, 1979).

V.B.5 Local Structural Geology

The TexCom WDW-315 AOR is located just north of the apex and covering much of the NW flank of the large Conroe Dome in Montgomery County, Texas. That flank of the dome demonstrates localized, counter-regional north dip decreasing away from the dome's apex until it flattens and returns to regional south dip off the northern edge of the field. In the AOR, dip is uniform except in the vicinity of scattered faults related to salt movement at the core of the dome. The largest of these faults is the East – West trending down-to-the-basin apparent in Figure V.B.1.6. This fault displays between 100 feet to 150 feet of throw depending upon

location. The fault decreases in throw to toward the edges of the dome. The original oil/water contact was the same on both sides of the fault suggesting that sands communicated across the fault zone.

A second, parallel fault is mapped at the extreme southern edge of the AOR. This fault exhibits up to approximately 75 feet of down-to-the-basin throw. Both of these parallel faults appear to be extensional features formed shortly after growth of the salt piercement structure at the core of the dome. These are the only mapped faults in the AOR although there may be others with little vertical throw that exist in the area.

V.B.6 Local Fault Transmissivity

The transmissivity of fluids across local faults will likely be much lower where the faults cut thick marine mudstones and shales than where the faults cut the sand packages of the Upper, Middle, and Lower Cockfield Sand Members. The higher permeabilities in the sand packages allow the faults running through those units to be more open to fluid flow. Mudstones and shales, especially those of the Upper and Lower Confining Zones, have low levels of induration and strength; faults through the mudstones would not be open to fluid flow.

V.B.7 Confining Zone Faults and Fractures

The Upper and Lower Confining Zones are discussed in detail in Section **V.B.1.b**.

V.B.8 Confining Zone Lithologic and Stress Characteristics

The Upper and Lower Confining Zones show little induration in the WDW-315 well. These Eocene age mudstones do not possess sufficient strength to transmit stress over large distances. Stress fields in the AOR, at the same time, should be minor or non-existent, depending upon movement of the Conroe Dome salt mass. As discussed in Section **V.A.5 and V.A.6**, movement on the salt mass is driven by sediment loading in the area. The area has been stable since the Pleistocene, neither receiving sediment nor experiencing extensive erosion. The salt mass at the core of the Conroe structure should also be stable.

V.B.9 Definition and Description of Buffer Aquifers

Buffer aquifers above the Upper Confining Zone are discussed in Section **V.B.3.a.iv**.

V.B.10 Local Seismic History

Historical seismic activity is discussed in detail in Section **V.A.6**.

V.B.11 Surface Geology

Surface geology is discussed in detail in Section **V.B.**

V.C Well Logs

Clean copies of the well logs in the AOR that penetrate the Injection Interval at an approximate scale of 1 inch equal to 100 vertical log feet, **are included in the Appendix.**

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